

FAINT SOURCE COUNTS FROM THE OFF-SOURCE FLUCTUATION ANALYSIS ON THE DEEPEST CHANDRA FIELDS

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ABSTRACT

We show the results of the fluctuation analysis applied to the off-source areas from the two 1 Million second *Chandra* Deep Fields, including our new results on the Chandra Deep Field-South (CDF-S) in the 0.5-2 keV band in addition to those on the Chandra Deep Field-North (CDF-N), which have already been reported. The distribution of the X-ray counts in cells has been compared with the expectation from the $\text{Log } N - \text{Log } S$ model to constrain the behavior of the source number density down to a factor of several lower than the source-detection limit. We show that our results are insensitive to the non-uniformity of the non X-ray background (NXB). Our results show that the number counts in the soft band (0.5-2 [keV]) continue to grow down to $S_x \sim 7 \times 10^{-18} [\text{ergs}^{-1} \text{cm}^{-2}]$, possibly suggesting the emergence of a new population and they agree well with a prediction of star forming galaxies.

Key words: galaxies: active—galaxies: evolution— (cosmology:)diffuse radiation—X-rays:diffuse background

1. INTRODUCTION

The number densities of X-ray sources as a function of flux (the so called the $\text{Log } N - \text{Log } S$ relation) is one of the key constraints for models of the X-ray source population. Most of the “Cosmic X-ray Background” (CXRB) intensity has now been resolved with “Chandra” (Muhsotzky et al. 2000; Rosati et al. 2001; Brandt et al. 2001) to the extent that major uncertainties in the fraction of the CXRB which have been resolved into individual sources, i.e, how much of it remains to be explained, lie in the absolute intensity of the CXRB and field-to-field fluctuations due to cosmic variance. In terms of the origin of the CXRB, the faintest sources in the *Chandra* Deep Fields are becoming less interesting. However, constraints on number counts at the faintest possible fluxes provide a new view on the nature and evolution of the X-ray emitting sources.

Fluctuation analysis is a strong tool for constraining the number densities of sources which are fainter than the source detection limit. This technique, which has been pioneered in radio astronomy (e.g. Condon 1974), has also been successfully applied to the X-ray data from previous missions (e.g. Hamilton & Helfand 1987; Hasinger et al.

1993; Georgantopoulos et al. 1993; Gendreau et al. 1998, Yamashita et al. 2000; Perri & Giommi. 2000). The source counts inferred from these analyses have turned out to be consistent with those from resolved sources in deeper observations later. Initial results of our work on CDF-N has been reported in Miyaji & Griffiths (2002) (hereafter, MG02). In these proceedings, we also report our new result on the 0.5-2 keV result on CDF-S, which gave a consistent result, but more tightly constrained.

We also discuss a number of technical issues which have not been explained in MG02.

2. IMAGE SIMULATION AND STATISTICS

The analysis has been made by comparing the count distribution of $4'' \times 4''$ image cells ($P(D)$ distribution) in the real data and the model. Because the point spread function (PSF) and exposure varies over the ACIS field of view (FOV), analytical modeling of the $P(D)$ distribution cannot be used. Also because the probability distribution of the $P(D)$ curve for a given model involves the fluctuations of both photon counts and source counts, it does not follow the simple Poisson statistics. Thanks to the rapid improvements in computing power in recent years, massive Monte-Carlo simulations can be made on our desktops for (1) modeling the $P(D)$ distribution, and (2) searching for the 90% confidence range of the $\text{Log } N - \text{Log } S$ relation.

For this purpose, we have developed an image simulator (*qimsim*), which can quickly simulate the summed image from multiple pointings of Chandra observations and allows one to analyze the statistics of simulated images. *Qimsim* generates randomly placed point sources for a given $\text{Log } N - \text{Log } S$ model. For each source generated at a sky position and for each pointing, it generates events based on the exposure map and the off-axis angle from the pointing direction. This is repeated for all the pointings used for the summed image. We assume that the background events are dominated by non X-ray (particle) background (NXB). The NXB is generated using a separate “NXB distribution map” (see below) in such a way that the total of the simulated source and the NXB counts is equal to that of the real data.

To assess the significance of the difference between the model $P(D)$ (the mean of the $P(D)$ curves from the 1000 simulations) and that of the observation, we have used Monte-Carlo simulations. For this purpose, we can use any

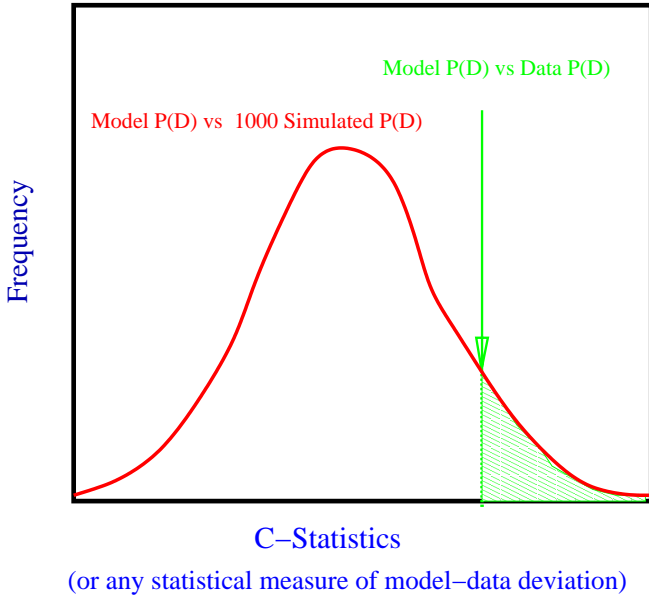


Figure 1. The assessment of acceptability of a $\text{Log } N - \text{Log } S$ model using the Monte-Carlo simulations is illustrated. The solid curve is the distribution of C_{sim} (see text) for the 1000 simulations. The spread of C_{sim} is caused by the statistical fluctuations of both the X-ray sources and the detected events. If C_{sim} exceeds C_{obs} in 10% of the simulations or more (hatched area), we have accepted the model and included in drawing the 90% confidence fluctuation “horn”.

quantity measuring the difference between the model and the data. For this purpose, we use the Cash modification of the Cash-C statistics (Arnaud & Dorman 2001; Cash 1979; see also MG02). The acceptance probability has been assessed as follows:

1. Calculate the distribution of the 1000 C_{sim} values between the model $P(D)$ and the 1000 simulated $P(D)$ distributions derived from the same set of model parameters.
2. Calculate C_{obs} between the data and the model.
3. The fraction of the C_{sim} values which exceed C_{obs} is taken as the model acceptance probability.
4. If this fraction is > 0.1 , we accept it. From the points in the model parameter space which have been accepted, we calculate the 90% confidence “horn”.

This procedure is illustrated in Fig. 1.

We plan to use the simulator for further studies involving angular correlation functions.

3. FLUCTUATION RESULTS, AGNs AND GALAXIES

3.1. RESULTS

As we see in MG02, we could only obtain loose constraints on the 2-10 keV band for CDF-N, mainly because of the

high NXB and limited area of analysis. In these proceedings, we concentrate our discussion on the 0.5-2 keV band. Fig. 2 shows the 0.5-2 keV $\text{Log } N - \text{Log } S$ relations for the CDF-N fluctuation, CDF-N resolved sources (MG02) and the new fluctuation result from CDF-S.¹ The method of the CDF-S analysis is essentially the same as that of CDF-N reported in MG02. Since the pointing directions are much more concentrated in the CDF-S data than the CDF-N case, we used the single circle of $5/2$ around the exposure-weighted mean pointing direction for our analysis. We have also included the *resolved source* constraint at $S_x = 9 \times 10^{-17} \text{ [erg s}^{-1} \text{ cm}^{-2}]$ from the resolved source count and the 1σ error from Rosati et al. (2001) (see MG02 for the detailed explanation on incorporating the *resolved source constraint* into analysis). Fig. 2 shows that the faint number counts of CDF-N and CDF-S are consistent with each other, but CDF-S gave a better constraint, probably because we can utilize a larger area for analysis.

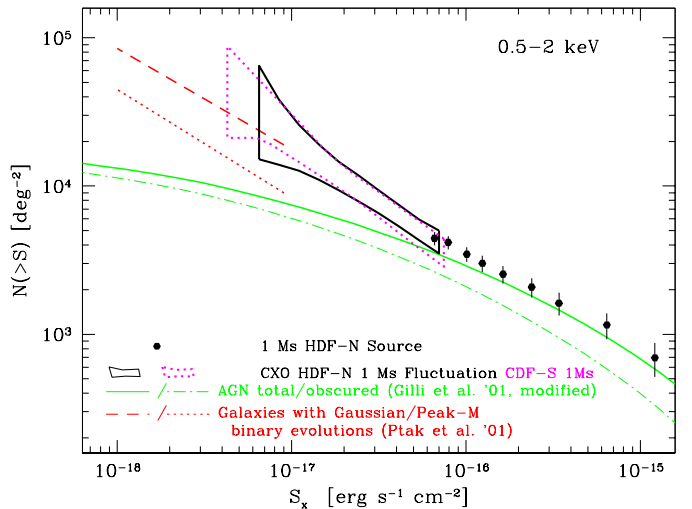


Figure 2. The derived $\text{Log } N - \text{Log } S$ relations (90% confidence “horns”) in the soft band in the CDF North and South are compared with AGN and galaxy number count models.

Predictions from the population synthesis model (B) by Gilli et al. (2001) for the total AGN population and the obscured ($N_{\text{H}} > 10^{22} \text{ [cm}^{-2}]$). Predicted number counts of galaxies using the cosmic star-formation history and two models (Gaussian and Peak-M) of evolution of X-ray binaries by Ptak et al. (2001) are also plotted. If mode B of Gilli et al. (2001) represents the correct behavior of absorbed and unabsorbed AGNs, the fluctuation constraints suggest the emergence of an additional population, probably from these galaxies.

¹ Machine readable ASCII tables of the fluctuation horns for our analysis on CDF-N/S can be found at <http://astrophysics.phys.cmu.edu/~deepxray/tables>.

We have overplotted the 0.5-2 keV $\text{Log } N - \text{Log } S$ prediction from the AGN population synthesis model composed of unabsorbed and absorbed AGNs based on by Gilli et al. (2001) (model B). The plotted model have been slightly modified from the original as described in Rosati et al. (2001). The curves for the total and absorbed ($N_{\text{H}} > 22 \text{ [cm}^{-2}\text{]}$) AGN populations are plotted. Fig.2 shows that the AGN counts drop below $S_x \sim 10^{-16} \text{ [erg s}^{-1} \text{ cm}^{-2}\text{]}$ even if the emergence of the obscured AGN population is taken into account, while the source counts from the fluctuation analysis continue to grow. If their model B closely represents the true behavior of the SXLf of the AGN population, we are probably seeing the emergence of a new population of faint X-ray sources. This excess may be contributed by AGNs with low intrinsic luminosities (at $L_x \lesssim 10^{41.5} \text{ [erg s}^{-1}\text{]}$) and/or X-rays from star-formation activities through supernova remnants and low-/high- mass X-ray binaries. In view of this, we have also overplotted a model prediction of X-ray number counts based on the cosmic star-formation rate Ptak et al. (2001) for the two models of binary evolution (Gaussian and Peak-M) from Ghosh & White (2001). Within the uncertainties in the AGN source counts and model construction, these predictions gave approximately the number counts from our fluctuation analysis.

3.2. SENSITIVITY TO NON-UNIFORM NXB

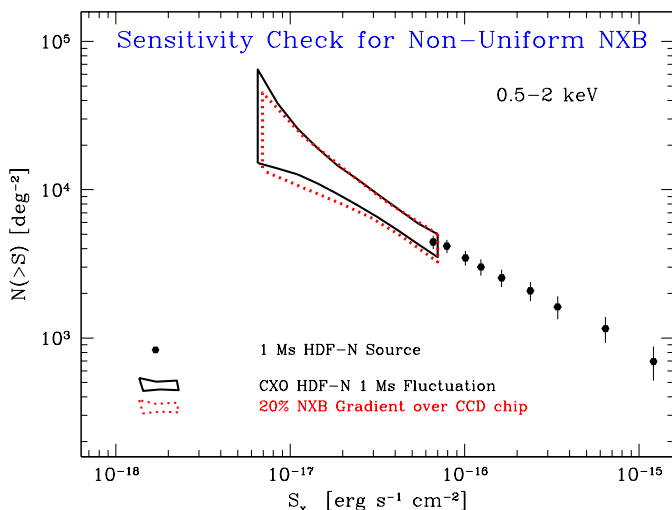


Figure 3. Sensitivity to the NXB non uniformity has been assessed. The solid curve assumes that the NXB is uniform over the active region of the CCD and dotted curve assumes that the NXB has a 20% gradient across the ACIS-I CCD chips. The comparison of these two shows that our analysis is not sensitive to the non-uniform NXB level.

It has been reported that the non X-ray background (NXB) varies over the ACIS CCD-chip at the level of $\sim 20 - 30\%$ across the ACIS-I chip for $E > 5 \text{ keV}$, while the variation is much less for lower energies.² While we treated NXB uniform over the active region in our analysis, one may worry that this NXB non uniformity could cause an overestimate of the derived $\text{Log } N - \text{Log } S$ relation. Thus we have also made the analysis assuming that the NXB has a 20% gradient along the CHIP-Y coordinate by adjusting the NXB distribution map. The results for the uniform and “slope” NXB are compared in Fig. 3. Fig. 3 shows that the systematic error caused by this effect is much smaller than statistical errors.

4. SUMMARY

1. Fluctuation analyses have been made on the two 1 Ms Chandra observations on the CDF-North and South in order to constrain the behavior of the $\text{Log } N - \text{Log } S$ at fluxes fainter than the source detection limit. We also show our new results on CDF-S for the soft band.
2. We have used Monte-Carlo simulations to obtain model-predicted $P(D)$ curves and evaluate the 90% confidence constraints.
3. The number counts in the soft band (0.5-2 [keV]) continues to grow down to $S_x \sim 7 \times 10^{-18} \text{ [erg s}^{-1} \text{ cm}^{-2}\text{]}$, suggesting the emergence of a new population, possibly X-rays from star-formation activity.
4. The impact of non uniformity of the non X-ray background on our $\text{Log } N - \text{Log } S$ is much smaller than the statistical errors.

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REFERENCES

- Arnaud, K., & Dorman, B. 2001, XSPEC Users Guide for version 11.1.x
 Brandt, W.N., et al., 2001, AJ, 122, 2810
 Cash, W. 1979, ApJ, 228, 939
 Condon, J. J. 1974, ApJ, 188, 27
 Gendreau, K.C., Barcons, X., & Fabian, A.C. 1998, MNRAS, 297, 41
 Ghosh, P. & White, N.E. 2001, ApJ, 559, L97
 Georgantopoulos, I., Stewart, G. C., Shanks, T., Griffiths, R. E., & Boyle, B. J. 1993, MNRAS, 262, 619
 Gilli, R., Salvati, M., & Hasinger, G. 2001, A&A, 366, 407
 Hamilton, T. T. & Helfand, D. J. 1987, ApJ, 318, 93
 Hasinger, G., Burg, R., Giacconi, R., Hartner, G., Schmidt, M., Trumper, J., & Zamorani, G. 1993, A&A, 275, 1
 Miyaji, T., Griffiths, R.E. 2002, ApJ 564, L5 (MG02)

² See <http://cxc.harvard.edu/contrib/maxim/bg/index.html>

- Mushotzky, R.F., Cowie, L.L., Barger, A.J.& Arnaud, K. A.
2000, *Nature*, 404, 459
- Perri, M. & Giommi, P. 2000, *A&A* 362, L57
- Ptak, A., Griffiths, R.E., White, N.E., & Ghosh, P. 2001, *ApJ*,
559, L91
- Rosati, P. et al. 2001, *ApJ* in press (astro-ph/0110452)
- Yamashita, A. 1999, Doctoral Thesis, University of Tokyo